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Operations Review of June 14, 2000 PG&E Bay Area System Events Using *Aempfast* ® Software

CONSULTANT REPORT

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PUBLIC INTEREST ENERGY RESEARCH
"Research Powers the Future"

Operations Review of June 14, 2000 PG&E Bay Area System Events Using *Aempfast*® Software

Final Report

October 3, 2001

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Optimal Technologies (USA) Inc. (Optimal) has prepared this FInal Report under contract to the Lawrence Berkeley National Laboratory (LBNL) and the California Energy Commission (CEC), with the supervision and cooperation of the California Independent System Operator (Cal ISO) and the participation of Pacific Gas & Electric (PG&E). The contract is funded under the Consortia for Electric Reliability Technology Systems (CERTS) Project.

The report demonstrates the application of Optimal's new Aempfast technology for analysis of certain June 14, 2000 PG&E system conditions as represented in data sets provided to Optimal by Cal ISO and PG&E. The report responds to specific tasks related to such conditions posed to Optimal by the contracting agencies. The Aempfast software Optimal has used for this analysis is currently under Advanced Beta status, and will be commercially available upon completion of Intellectual Property procedures now in progress.

NOTICE

The analytic methodologies Optimal has applied in preparing the report represent Optimal's professional judgments alone. The Final Report's conclusions are based on the specific data analyzed, and incorporate all materials presented in the Final Report. Optimal provides the report and its conclusions solely for the purpose of demonstrating certain of Aempfast's capabilities, and expressly intends that they not be used for any other application. Any other use of or reliance upon the report or its conclusions by any person is the responsibility of such person alone, and Optimal accepts no responsibility therefor.

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Aempfast Evaluation Task Final Report

Executive Summary

The California Energy Commission (CEC) and the Lawrence Berkeley National Laboratory (LBNL) asked Optimal Technologies (USA) Inc. to apply Optimal's proprietary *Aempfast*® *(*"Aim-fast"*)* network optimization software to perform a detailed review of conditions on the Pacific Gas & Electric (PG&E) electric power system and Bay Area power system at the time of the June 14, 2000 impending collapse of the Bay Area System and the emergency rotating blackout of over 140 MW (approximately 100,000 homes and businesses). The principal purpose of the study was to evaluate Aempfast's capabilities by applying it to well documented circumstances in which a power system was under acute stress. The CEC, LBNL, California ISO, and PG&E provided the data to be analyzed, and personnel to serve as a Technical Review Committee.

Optimal was asked to use Aempfast to review certain decisions Cal ISO and PG&E made on June 14, 2000 regarding the amount of load shed necessary to have prevented voltage collapse on the Bay Area System, the proper location for monitoring system voltage levels, and the correct voltage level trigger point for ordering emergency load shedding to prevent system collapse. Optimal was to assume the availability and control only of system resources available to Cal ISO and PG&E on that date.

Among its numerous applications, Aempfast can swiftly analyze conditions on any power network to determine, in detail,

(i) points of inefficiency and congestion in the network;

(ii) specific solutions for minimizing such conditions and optimizing system conditions to improve voltage stability, voltage profile, power flows, and power quality delivered;

(iii) real and reactive power resources and transmission resources needed for system optimization; and

(iv) the exact network location for optimal placement or shed of any source or load (real or reactive power), or for other resources.

Using Aempfast, Optimal found that on June 14, 2000 **the Bay Area System in fact had sufficient generation and other resources (including transmission and distribution resources) to have withstood voltage collapse without any load shedding, had measures now identifiable using Aempfast been implemented**. Congestion and related PG&E System conditions precipitated Bay Area System voltage instability by inhibiting power flows in the System necessary to maintain voltage levels under the pressure of spiking hot-weather loads. The primary solutions Aempfast identified involve "re-controlling" of many of the over 400 PG&E System "control buses."[1] **Aempfast analysis indicated that the re-controlling measures would have fully supported system voltage stability, with some resources to spare, avoiding need for any load shed under the generation and load conditions of that day.**

Optimal found that with the tools and the data then available to them, Cal ISO and PG&E made appropriate decisions on June 14, 2000 regarding amount of load to be shed, system monitoring point, and voltage level at which to commence load shed.

Among Optimal's key findings was that poor system distribution of reactive power ("Q") resources,[2] as well as of real power ("P") resources,[3] contributed substantially to the impending voltage collapse under June 14 loads. Aempfast optimization resulted in significant reductions in System network losses for both real (P) and reactive (Q) reactive power, and in improved P and Q

1. See footnote 6 on page 10 for a discussion of "control buses."

power flows, voltage stability, voltage profile, and power quality throughout the Bay Area System. After Aempfast optimization, the Bay Area System was stable not only under the June 14, 2000 loads but also under test loads of 130.4 MW that, at the request of the Technical Review Committee, Optimal applied over and above the June 14, 2000 load levels.

Optimal's system optimization results using Aempfast are verifiable by running the reconfigured system data through conventional system display, presentation, and monitoring tools.

At the additional request of the Technical Review Committee, Optimal also demonstrated the manner in which Aempfast would have ranked the most effective loads for shedding (i.e., loads the shedding of which would have provided most support for the Bay Area System) in the event of need for load shed measures.

2. "Q" is the designation for "reactive power", which is measured in "VAr" and "megaVAr" (MVAr). Reactive power resources in an electric power system are critical to maintaining system voltage stability. Although of critical importance, the role of reactive power ("Q") in maintaining a healthy power system and the adequacy of reactive power resources in a system are little understood and are rarely addressed in policy reviews and public debates regarding electric power system performance.

3. "P" is the designation used in electrical engineering for "real power", which typically is measured in watts, kilowatts, and megawatts (MW). Virtually all public debate and discussion of electric power focuses on P resources.

1 Introduction: Scope of Work; Participants; Project Schedule

Optimal Technologies (USA) Inc. (“Optimal,” “the Company”) submits this Final Report in fulfillment of its Subcontract No. 6510462, “June 14, 2000 Operations Review Using Optimal Technologies (USA) Inc.’s *Aempfast*® Software” (the “Project’) with Lawrence Berkeley National Laboratory (“LBNL”) and the California Energy Commission (“CEC”). Specifically, this Final Report fulfills Task 7 of the Tasks/Timing section of the Subcontract’s Scope of Work.

This Final Report presents description and discussion of (i) the performance capabilities of Aempfast (pronounced “Aim-fast”), Optimal’s proprietary advanced power flow analysis and optimization technology; (ii) the study tasks LBNL and CEC have commissioned at the several phases of the study; (iii) the specific data supplied to Optimal on which the study was based; (iv) the methodology Optimal has employed in applying Aempfast to the several study tasks; and (v) the results of the final study phase.

In the June 14, 2000 event under study (the “June 14 event”), the California ISO (Cal ISO) was faced with rapidly falling voltage levels at a key PG&E Bay Area system bus, indicating imminent system collapse due to insufficient voltage support. Cal ISO (a) ordered PG&E to shed firm Bay Area loads of over 140 MW, which PG&E accomplished in rotating outages over a three-hour period affecting approximately 100,000 residential and small business customers; (b) accepted 9 MW additional load shed from municipals; and (c) loaded key 500/230 kV transformers and transmission lines either near or in excess of their ratings. Earlier in the day, the ISO also had required PG&E and Bay Area municipals to increase reactive support at the transmission and distribution levels. A summary description of the June 14, 2000 operating event, excerpted from an official report to the Governor of California, is presented as “Excerpts from EOB/CPUC Report to Governor Davis” on page 29 to this report.

Optimal has performed all final optimization and analytic tasks using Aempfast exclusively. The results presented are based on the data supplied by the California ISO and the assumptions included in the Methodology section of this report. Any change to the data supplied, or any significant change in these assumptions, will void the conclusions presented here and require a re-analysis.

1.1 Technical Scope of Work

1.1.1 Original Scope Of Work

The original Scope Of Work for the Project (subsequently augmented and altered as described below) was as follows:

“Optimal shall, using *Aempfast*, perform a detailed study of the June 14, 2000 operating day on the PG&E power grid when the ISO requested PG&E to drop 130 MW of load to prevent voltage collapse in the Bay Area.”

1.1.1.1 Original Study Questions

The original Scope of Work (June 6, 2001) directed that the study address the following questions relative to the June 14, 2000 operating day events:

1.1.1.1.a “Could PG&E have shed less than 130 MW of load and still have guaranteed there would not be a voltage collapse?”

1.1.1.1.b “Which voltage should we [Cal ISO and PG&E] have been monitoring to determine voltage collapse was imminent?”

1.1.1.1.c “Was 227 V the correct trigger point for calling for manual load shedding?”

1.1.1.2 Original Study Conditions, Assumptions, and Constraints

Optimal and the other Study Participants understood that the following constraints were to be applied:

1.1.1.2.a As described in Table 2, "Bay Area System by Zones (Data Provided Post-August 22, 2001)," on page 18 ("Bay Area System," System), Optimal was to focus on voltage stability conditions and load shedding options within the Bay Area System component of the PG&E system (as defined by PG&E), rather than on the entire PG&E grid;

1.1.1.2.b Question 1 was addressed to real power ("P") loads only, not to reactive power ("Q") loads. [Note: But see Augmented Scope Of Work, below, re subsequent study task re both P and Q]; and

1.1.1.2.c In conducting its Aempfast analyses, Optimal was not to apply or assume any additional resources to the PG&E Bay Area System.

1.1.2 Augmented Scope Of Work

As a courtesy, but not as a matter of contract, Optimal agreed to undertake several additional analytical tasks invited by the Cal ISO and other Technical Reviewers following a July 24, 2001 meeting of the Study Project Technical Review Committee (the "July 24 tasks"). Optimal agreed to undertake the July 24 tasks and to report publicly on two of them. Certain other July 24 tasks Optimal agreed to undertake on a confidential basis only, subject to signed non-disclosure agreements, with results not for general publication, and for Aempfast technology evaluation purposes only (i.e., the data from these certain additional tasks are not to be used for any purpose other than technical evaluation of Aempfast). The July 24 tasks are described in the following section.

1.1.2.1 July 24, 2001 Additions to Original Scope of Work

At the July 24 interim meeting of the Participants, Cal ISO and PG&E asked that <u>in</u> <u>addition</u> to the original Scope Of Work tasks, Optimal perform the following additional tasks:

1.1.2.1.a <u>Add</u> an analytic task in which Bay Area load is increased using <u>both</u> real and reactive (P and Q power), while maintaining the value of the PF of Bay Area loads.

1.1.2.1.b <u>Add</u> an analytic task in which Optimal overloads the "swing bus"[4] real power component, and report the amount of Q still available on the swing bus for the P and Q tests only.

1.1.2.2 August 22, 2001 Additions to Original Scope of Work and July 24, 2001 Additions

At the August 22 interim meeting of the Technical Review Committee, at which Optimal presented the Draft Final Report, the Technical Reviewers requested that, in addition to the original Scope Of Work tasks and the July 24 tasks, Optimal make the following adjustments in preparing the Final Report (the "August 22 tasks"):

1.1.2.2.a In text and tables referencing individual buses, identify each bus by name as well as number, rather than by number only, for improved readability.

1.1.2.2.b Revise the Final Report as necessary to address all Bay Area Zones with conforming loads, in accordance with further clarification as provided by Cal ISO.

1.1.2.2.c Run and report final analyses using a PG&E June 14 data set with the Pittsburg 7 generator **NOT** on-line.

4. The "swing bus" is a special bus which is connected to, and thus identifies, the "swing generator." The output of all generators in a system is scheduled/fixed <u>except</u> that of the swing generator. Electrical power on a system cannot be stored, so power generated MUST always equal power consumed. As the load on the system changes/swings, the output of the swing generator follows the change to guarantee there is no imbalance.

Comment: Pittsburg 7 had been on-line and an available generator in the PG&E Bay Area System data set Cal ISO originally provided to Optimal.

1.2 Study Participants

Participants in the Study Project include the following:

1.2.1 Lawrence Berkeley National Laboratory (“LBNL”)

LBNL is the master contractor to CEC for the CERTS Project contract.

1.2.2 California Energy Commission (“CEC”)

CEC is the master contracting agency for certain research and development work being conducted under the Consortia for Electric Reliability Technology Systems (“CERTS”) Project. CEC senior transmission planning staff are Technical Reviewers of this study.

1.2.3 California Independent System Operator (“Cal ISO”)

Cal ISO is the operator of the California power grid (including the portion of the grid on which the June 14, 2000 event occurred), is a participant in CERTS, and is a primary technical reviewer of the Evaluation Task study. Cal ISO provided Optimal certain of the key data sets used in the study, and initiated a number of the requests for additional or altered tasks. Cal ISO senior grid planning staff are Technical Reviewers of this study.

1.2.4 Dr. Christopher L. DeMarco,

Dr. DeMarco is Professor of Electrical and Computer Engineering, University of Wisconsin. He is a CERTS Program associate and a Technical Reviewer of this study with expertise in optimal power flow (“OPF”) and voltage issues.

1.2.5 Optimal Technologies (USA) Inc.

Optimal is a subcontractor to LBNL. Optimal controls the Aempfast technology that is the subject of the Evaluation Task study, and is the entity responsible for performing the Evaluation Task study.

1.2.6 Pacific Gas & Electric Company (“PG&E”),

PG&E is the owner/manager of the portion of the distribution grid on which the June 14 event occurred. The PG&E distribution grid is the subject of this Evaluation Task study. A PG&E senior transmission planning staff engineer is a Technical Reviewer of the study.

1.3 Project Schedule

On June 8, 2001, the Project began with an organizational meeting at Cal ISO offices attended by representatives of each of the Participants. Cal ISO and PG&E forwarded system data for the Project to Optimal via email beginning June 11.

On July 12, 2001, Optimal submitted to all participants a “Preliminary Progress Report” entitled, “Evaluation of Optimal Technologies Aempfast Product Based Upon the June 14 2000 Event”. The Preliminary Progress Report described Optimal’s initial steps, set forth some questions regarding the PG&E Bay Area System and the data provided, and presented its early study results through the first approximately two weeks of active work.

On July 24, 2001 the Technical Review Committee met again at Cal ISO to discuss the Preliminary Progress Report and the remaining steps of the Project. Cal ISO and PG&E requested that the Scope of Work be augmented to include the July 24 tasks listed in Section 1.1.2.1 on page 8.

On August 22, 2001, the Technical Review Committee met to discuss the draft final findings and conclusions of the study, including responses to the three study questions, and to discuss the applications and performance of Aempfast in carrying out the Study. Cal ISO requested that the Scope of Work also perform the August 22 tasks listed in Section 1.1.2.2 on page 8.

Optimal now submits this Final Report on the Project.

2 Summary of Conclusions

This report addresses the original Scope of Work questions, the July 24 tasks for which the results are not confidential, and the August 22 task. Optimal has obtained the final results in this report exclusively through optimal power flow analysis using its proprietary Aempfast optimization and analysis software. The results presented are based on Aempfast optimization and analysis of final revised data provided by Cal ISO on or about August 22 (Dataset: 0614-8750-p7), and on the assumptions set forth in the section [4] entitled, "Methodology" on page 14 of this report.

2.1 Question 1

"Could PG&E have shed less than 130 MW of load and still have guaranteed there would not be a voltage collapse?"

2.1.1 Conclusion to Question 1

Using Aempfast, Optimal found that on June 14, 2000 the PG&E Bay Area System in fact had sufficient generation and other system resources (including transmission and distribution resources) to have withstood voltage collapse without any load shedding, had it been feasible with then-available tools to identify and implement certain critical PG&E System adjustments. Congestion and related System conditions precipitated Bay Area System voltage instability by inhibiting power flows in the System necessary to maintain voltage levels under the pressure of spiking hot-weather loads. In this study, Optimal applied Aempfast's Optimizer to June 14 PG&E System data supplied by Cal ISO to swiftly identify such System conditions and list specific, easily-accomplished measures for alleviating such conditions.[5] Aempfast analysis indicates that the measures so identified would have fully supported system voltage stability on the June 14 Bay Area System, with some resources to spare, avoiding need for any load shed under the generation and load conditions of that day.

The primary solutions Aempfast identified involve simple "re-controlling" of PG&E System "control buses."[6] The Aempfast Optimizer also identified one generator that was causing system congestion and could have been shut down to improve system power flows. For the purpose of this study, the generator was left running (i.e., unchanged from the data supplied). Consistent with the study directives, Optimal has included no resources that were not already immediately under the control of PG&E and Cal ISO at the time of the study event.

Aempfast optimization resulted in significant reductions in System network losses for both P (real) and Q (reactive) power, improved P and Q power flows in the Bay Area System, improved power quality in the Bay Area System, and improvements in voltage profile throughout the Bay Area Sys-

5. Optimal believes (but has not confirmed) that all measures identified for this study could have been implemented in the course of a few hours. Aempfast is capable of more fundamental system optimization involving measures that require equipment movement or adjustment or capital improvements, but these capabilities have not been used in this study.

6. In normal operation of a network, the voltage at one bus is fixed. The voltage at all other buses is determined by the physical parameters of the equipment used to conduct electric current throughout the network. Conversely, if the voltage at a second bus is fixed, the flow between the fixed buses will be increased or decreased and current will flow along alternate paths. A number of fixed voltage buses may be used to interfere with the normal flow of current, or stated otherwise, to control the flow of current in the network. The locations of control buses are strategically selected. Determining the voltage of each of the control buses is a mathematically complex problem, which must include considerations such as power quality and statutory requirements.

tem. After Aempfast optimization, the Bay Area System was stable not only under the June 14, 2000 loads but also under test loads of 130.4 MW that Optimal applied over and above the June 14, 2000 load levels. Although Aempfast clearly shows that after optimization no June 14 load shedding would have been required, Aempfast indeed is able to rank the most effective loads for shedding (i.e., loads the shedding of which would provide most support for the Bay Area System) in the event load shed measures were needed.

2.2 Question 2

“Which voltage should we [Cal ISO and PG&E] have been monitoring to determine voltage collapse was imminent?”

2.2.1 Conclusion to Question 2

The second goal of the study was to determine which PG&E Bay Area System bus was most sensitive to impending voltage collapse and therefore the appropriate bus for Cal ISO/PG&E monitoring. As noted above, after optimization as directed by Aempfast, the Bay Area System would not have been subjected to voltage collapse resulting from the June 14 loads. Thus Aempfast optimization in effect renders this specific question moot.

In Optimal’s study of stressing the non-optimized PG&E Bay Area System to the point of collapse, it reached full collapse at 216 kV on NEWARK D bus number 30630. During system collapse, voltage at this bus moved through a range of approximately 12 kV. This voltage drop exceeded 5%, reflecting strong sensitivity for a high voltage bus. Optimal believes this indicates that Newark D indeed was a good choice for use in monitoring the Bay Area System. No other buses at this voltage level showed a higher degree of sensitivity.

2.3 Question 3

“Was 227 V the correct trigger point for calling for manual load shedding?”

2.3.1 Conclusion to Question 3

As noted, after Bay Area System optimization using Aempfast, no load shedding at all would have been indicated. Optimal’s Aempfast analysis concludes that the June 14, 2000 Bay Area System could have been optimized to maintain voltage stability at 226 kV. This indicates that voltage shedding could have been delayed to the 225 kV level. Initiating load shed at 225 kV, however, would have been cutting the edge very close. Without the availability of a very accurate analytic tool such as Aempfast, it would have been unreasonable to attempt to maintain the Bay Area System at this level. Optimal concludes that, given the tools available to Cal ISO and PG&E at the time, 227 kV was a prudent point at which to begin manual load shed.

Note Regarding Tasks 4 - 7

The three study questions originally posed to Optimal were framed in terms of real power (P) only. The Aempfast Optimizer, however, typically selects as initial goals in an optimization both 1) minimizing P (real power) loss, and 2) minimizing Q (reactive power) loss. In addition, Optimal has built into Aempfast a fixed goal of strong enforcement of bus voltage limits. Aempfast will not readily allow a voltage limit to be violated at any bus. Aempfast, in its default operation, applies more emphasis to bus voltage limits than to any other goals.

Following the July 24 interim meeting, the Study Participants augmented the study tasks posed to Optimal to include additional analytical tasks focusing on both P and Q, as described below.

2.4 Additional Task 4

Add a criterion to the analyses such that the Bay Area System load is increased using both real and reactive (P and Q) power, in a manner that maintains the power factor ("PF") of all Bay Area loads.

2.4.1 Results of Additional Task 4

Optimal successfully conducted the requested additional analyses, increasing active and reactive load in the Bay Area zones while maintaining the power factor (PF) of loads.

2.5 Additional Task 5

Optimal was asked to conduct an exercise in which it would increase both P and Q loads in the Bay Area to levels that would cause an overload on the real power component of the swing generator [MORRO 4 (Bus 36410)], and to report the amount of Q still available on the swing generator at the P overload.[7]

2.5.1 Results of Additional Task 5

Optimal increased P and Q loads on the Aempfast-optimized Bay Area system by 3%, which resulted in overload of the swing generator real power (P) component by approximately 25% [i.e., 25% greater than its rated P generation capacity]. At these P overload conditions, approximately 41% of the total Q this bus can generate remained available. Detailed results are presented in the section [8.2.2] entitled, "Stress Testing: Safely Overloading the PG&E Bay Area System" on page 25 of this Report.

2.6 Additional Tasks 6 and 7

Provide Cal ISO (Task 6) and PG&E (Task 7) with "before" and "after" voltage values for all buses, including control and swing buses;

2.6.1 Conclusion to Additional Tasks 6 and 7

The "before" and "after" voltages for all buses, including control and swing buses, will be shown in an upcoming live presentation to Participants. In general, the "after optimization" bus voltages show that

2.6.1.0.a Aempfast has moved voltage magnitudes closer to the mean, and

2.6.1.0.b Aempfast has increased mean voltage magnitudes.

This clearly shows Aempfast's strong simultaneous enforcement of both voltage limits and minimum loss goals. (Both 2.6.1.0.a and 2.6.1.0.b fight voltage collapse, while 2.6.1.0.b also minimizes Bay Area System losses).

2.7 Verification of Optimal's Conclusions

For the purposes of facilitating verification of Aempfast results using display, presentation, and monitoring tools currently employed by the California ISO, the California Energy Commission (CEC), and PG&E, Optimal has configured its results for presentation using PSLF (Power Systems Load Flow). PSLF is a General Electric (GE) load flow package in common use throughout the utility industry, and used by Cal ISO, CEC, and PG&E. Separate from Aempfast, Optimal itself uses

7. The original Evaluation Task study was based upon a voltage collapse case (June 14, 2000). Thus both PG&E and CAISO expressed strong interest in whether, in the Aempfast-optimized Bay Area System, the swing generator would retain sufficient Q even at P overload to continue to defeat voltage collapse.

its own version of load flow for various purposes, including as a display and presentation tool and as a monitoring aid. GE's PSLF and Optimal's load flow packages produce identical results.

Although the results produced using Aempfast alone are always superior, running the output of Aempfast back into PSLF or other load flow provides a relatively easy verification method using current industry accepted tools.

3 Introduction to Aempfast Performance Capabilities

Among its many possible analytic applications, Aempfast has the capability to analyze any specific power network under study to swiftly determine, in detail, (i) the real and reactive resources needed for system optimization, and (ii) the exact network location for optimal placement of any source or load, whether real or reactive. Aempfast accomplishes this by using strong enforcement of voltage limits to decrease the number of voltage and flow violations on the subject network. In fact, Aempfast's methodology focuses heavily on total elimination of all voltage violations in a system. The potential addition of strategic resources to the PG&E Bay Area System as indicated by Aempfast is not included in the scope of this Evaluation Task study, but is to be fully included within a separate Task X.[8]

Generally described, Aempfast ranks and indexes every bus on a system according to system resource need, and for supply of both real power (P) and reactive power (Q). Aempfast thus is an ideal tool for determining exactly which loads on a power system are the primary contributors to voltage collapse. As a corollary, Aempfast also ranks and indexes all generators according to their ability to support and carry load and to help prevent voltage collapse.

Aempfast also ranks and indexes all buses on the subject network according to the amount of "stress" placed on each of them to meet system-wide operational voltage limits. Therefore, Aempfast is an excellent tool for use in identifying sensitive buses.

Aempfast tightly and simultaneously links optimization of the subject system (i.e., optimized voltage stability and power flow) with full and comprehensive measurement of system resources: i.e., in optimizing the use of system resources, Aempfast analyzes the available real power (P) and reactive power (Q) resources at each and every bus of the system.

It should be noted that while this Evaluation Task study involves system optimization for active and reactive loads and resources, Aempfast also has been designed to analyze and optimize simultaneously for multiple competing system goals, including such other possible goals as generator dispatch based on fuel economy, minimum air emissions, minimum water release or consumption, etc. Aempfast can also be applied to optimize an entire power network of any size (small or large) while making such determinations as (1) proper order of retirement of older generating units based on fuel economy, air emissions, net contribution to system stability, power quality, and power flow, etc.; (2) proper ranking of possible additions to system resources (P and Q generators, capacitors, transformers, transmission and distribution lines, etc.) based on, e.g., capital cost per unit of net contribution to system stability and power flow, etc.; or (3) possible improvements to locations at which devices must be located. In addition, Aempfast can be used to determine accurate locational and marginal based pricing levels and to evaluate power sale contract terms based on the net system effect (i.e., effect on system-wide voltage stability and power flow) of the specific power source and supply in question.

By extension, it can be understood that Aempfast can be applied for advanced contingency planning for electric power infrastructure security (e.g., planning of cost-effective system redundancies, emergency alternate routing, advanced analysis of system capacities and resiliencies), for effec-

8. With the cooperation and support of Cal ISO and the California Energy Commission, Optimal has initiated Task X, "Aempfast Analysis of the PG&E San Francisco Bay Area Grid, 2002 Summer Peak Case: Optimization for Transmission Efficiency and Electric System Reliability (Voltage Stability. Preliminary recommendations are expected to be made available to Cal ISO and CEC in early November, 2001.

tive emergency response to unplanned emergency outage at any point of a system, and for optimized order of system repair and maintenance decisions following emergency events.

Similarly, it can be understood that in combination with enhanced system (including all loads) data monitoring and reporting equipment (SCADA systems) on any electric power network, Aempfast ultimately can provide a platform for real-time, end-to-end operation of the network.

Aempfast thus has many potential applications to both network operating and planning activities -- and, in fact, Optimal believes Aempfast's speed, scope, and multiple functions allow creative "bridging" of the traditional gap between electric system operators, planners, and market participants.

4 Methodology

This section describes the PG&E Bay Area System under study and the studies Optimal has performed. The conclusions ultimately presented are based on the assumptions and methodology set forth in this section. Any change to the data supplied, or any significant change in these assumptions, will void the conclusions presented here and require a re-analysis.

4.0.1 Initial Study Guidelines

As outlined briefly above, initially the study was to be conducted under the following guidelines:

4.0.1.a In conducting its Aempfast analyses, Optimal was to focus on conditions within the "Bay Area" of the PG&E system (as defined by PG&E), rather than on the entire PG&E grid. The "Bay Area System" is described in Table 2, "Bay Area System by Zones (Data Provided Post-August 22, 2001)," on page 18.

4.0.1.b In addressing Question 1, Optimal was to address real power (P) only, and not reactive power (Q) as well. This was changed after the July 24 interim meeting.

4.0.1.c In conducting its Aempfast analyses, Optimal was not to apply or assume any resource additions or changes ("mitigations") to the Bay Area System not otherwise available to the Cal ISO at the time of this incident.

4.0.1.d Optimal was to add an analytic task in which loads are increased using both real and reactive (P and Q power), while maintaining the value of the Power Factor (PF) of the loads.

4.0.2 Changes as a result of July 24, 2001 Interim Report

4.0.2.1 Reactive Power (Q)

As outlined above, the revised Study Guidelines added to the Study Guidelines the requirement to address reactive power (Q) as well as active power (P).

4.0.2.2 Swing Bus

As outlined above, Cal ISO asked Optimal to overload the swing bus real power component, and to report the amount of Q still available on the swing bus.

4.0.3 Changes As a Result of August 24, 2001 Draft Final Report

4.0.3.1 Bay Area Zones

The Study Guidelines asked Optimal to revise the power network analyzed as necessary to include all Bay Area Zones (the Bay Area System) with conforming loads, re-run the analyses, and revise the Final Report as appropriate. The Bay Area System consists of conforming zones shown in Table 2 on page 18.

Large electrical networks such as that coordinated by the Western System Coordinating Council are divided into areas based on both engineering and administrative criteria. All data is organized according to area. For example, PG&E is area 30 in the WSCC network.

PG&E in turn subdivides and organizes its network data into areas. The areas are further subdivided into zones (referred to as “area zones”). In the PG&E system there are 2 to 4 area zones per area.

Optimal utilizes its program “preproc” (preliminary processing) to deal with areas and zones as befits the task.

The PG&E “Bay Area System” that Optimal is asked to address in the Evaluation Task is not discretely defined in the data bases supplied. It consists of area zones disaggregated and assembled from different areas. Optimal modified its preproc routine to cut across areas and to select those area zones that together meet the given description of the Bay Area.

4.0.3.2 Pittsburg 7 Generator -- Off-line

The revised Study Guidelines asked Optimal to revise the June 14, 2000 network data set originally provided by removing Pittsburg 7 (two units of 53 and 54 MW, respectively) from the list of available generators, and to re-run the analyses and revise the Final Report as appropriate. Cal ISO provided Optimal a new data set for the PG&E Bay Area System that included the removal of the Pittsburg 7 generator. This required reprocessing of the new PG&E Bay Area System data with Aempfast, and consequent changes to the Final Report.

4.1 Overview of Methodology

4.1.1 Basic Study Methodology

Optimal’s basic procedures for the Evaluation Task study and data handling for the evaluation were as follows:

4.1.1.a Convert the supplied June 14, 2000 data from epc to cwf format.

4.1.1.b Partition the network to study the PG&E Bay Area System (area 30) only.

4.1.1.c Run standard load flow on the supplied (un-optimized) June 14, 2000 data to establish the base case for the purpose of comparing the base case with the subsequent Aempfast-optimized Bay Area System.

4.1.1.d Run load flow using the supplied (un-optimized) June 14, 2000 data, applying increasing load to establish the load at which voltage collapse occurs on the network. The increase in load is to be applied to the Bay Area portion of the un-optimized PG&E network only, and is to be in the form of real power (P) only.

4.1.1.e Run the Aempfast Optimizer on the supplied June 14, 2000 data to produce an optimized PG&E network, in order to determine the network indices for analysis purposes. Use only those indices that identify and rank buses for load shedding. Add no network resources.

4.1.1.f Run load flow on the optimized Bay Area System data.

4.1.1.g Run load flow on the optimized data while applying increasing load to establish the load at which voltage collapse occurs on the un-optimized network. The increase in load is to be applied to the Bay Area System of the PG&E network only, and is to be in the form of real power (P) load only.

4.1.1.h Run load flow on the optimized Bay Area System data. Use indices obtained from the Aempfast Optimizer to determine the load shed required to prevent voltage collapse.

4.1.1.i Use Aempfast indices to compare Bay Area bus to NEWARK D bus (30630) sensitivity.

4.1.1.j Rerun load flow on the original data with load shed as determined by steps 4.1.1.d to 4.1.1.h.

4.1.2 Changes to Basic Study Methodology

Following the July 24 interim meeting and the additional requests for analysis by Cal ISO and PG&E, Optimal made changes to the original basic procedure as follows:

4.1.2.a Added criteria to the tests such that the load on the optimized PG&E Bay Area System was increased using both real and reactive (P & Q) power, in a manner that maintained power factors of all loads.

4.1.2.b Overloaded the swing generator on the PG&E Bay Area system to approximately 125% of its rated P capacity by increasing P and Q loads in the Bay Area by 3 percent, and reported the amount of Q still available on the swing bus.

4.2 System Modeling

4.2.1 Assumptions

For purposes of this study, Optimal has assumed that flow violations occurring on the PG&E system are tolerable. Optimal has applied voltage limits of +/- 5% for all buses below 400kV, and +10% for all buses above 400kV.

4.2.2 Software Development for Network Model Conversion

As noted above, the Aempfast system uses a data format called “CWF”. The base cases provided to Optimal for this study are in the more widely used GE PSLF “EPC” format. In all cases, Optimal performs a conversion of EPC datasets to the CWF format. Then Optimal runs an initial load flow analysis on the converted network data. Finally, Optimal runs a system check (using Optimal’s “check-sys” software program) to ensure correct data conversion, compares the CWF output to the original EPC dataset to detect any possible conversion errors, and runs an initial load flow to establish a common, reproducible baseline before executing Aempfast.

In the Evaluation Task study, Optimal thus converted the data in the original .epc file to .cwf format, then ran it through one of Aempfast's built-in auxiliary load flow packages.[9] Optimal has built into Aempfast a number of such load flow and other proprietary auxiliary programs.[10] Two of these programs are “check-sys” and “check-sys-cpc.”

Optimal uses the check-sys and check-sys-cpc packages in combination to focus on individual lines connected to each bus. This forms a double check on the data conversion. In this study, a specific purpose of such application was to compare the results from the PSLF model for long 500 kV lines with the Aempfast model for long lines. The differences between the two models, if any, were shown to be insignificant.

4.2.2.1 check-sys

Optimal uses “check-sys” to compute the power flow to each individual bus in the network directly from the CWF data file. As a condition for correct conversion from EPC to CWF, power flow into each and every bus must be zero.[11]

9. The Aempfast suite of auxiliary products contains load flow packages reflecting three standard load flow techniques: Fast Decoupled, Newton, and Newton-Decoupled. [Note: GE’s PSLF is also based on standardized load flow.]
10. In the course of this study, Optimal has expanded the capabilities of these packages in order to meet the unique needs of the Evaluation Task.

4.2.2.2 check-sys-cpc

"Check-sys-cpc" calculates the power flows within the network using EPC input data. Check-sys-cpc is a recent addition to Aempfast's built-in capabilities. Optimal performed significant work on check-sys-cpc for this Evaluation Task, as a means of assuring accurate partitioning of the PG&E Bay Area System from the WSCC system data provided.

4.2.2.3 Program Development for Loading Criteria

One of Aempfast's proprietary auxiliary routines selects areas for file editing. As described in Section 4.0.3.1 on page 14, one of its editing features allows selection of areas for loading. In the Evaluation Task, Optimal has further extended this feature to allow re-grouping and processing of "area zones" as well as "areas".[12] This automatically extends all editing features to "area zones."

4.3 Study Phases

Optimal has conducted this study in four phases.

TABLE 1 Study Phases

Dataset Processed: Cal ISO file -0614-8750-p7.epc	
Phase	**Description**
1	Initial Load Flow
2	Baseline Bay Area System Analysis
3	Bay Area System Loading
4	Further Bay Area System Improvements

4.3.1 Study Phase 1 - Initial Load Flow

Phase 1 establishes the initial network conditions under load flow. Optimal runs the input system (the converted data) through Aempfast's auxiliary load flow package and captures the resulting voltage profile. Optimal uses these baseline conditions as a basis for comparison for later network analyses and suggested modifications.

4.3.2 Study Phase 2 - Baseline Bay Area System Analysis

The purpose of Phase 2 is to improve Bay Area System operation using the Aempfast analysis tools, but using only active and reactive resources available to Cal ISO and PG&E on June 14, 2000. Consistent with the study directives, Optimal has included no resources that were not already immediately available to PG&E and Cal ISO at the time of the study event.

Comment: The addition of strategic resources as indicated by Aempfast is not included in the scope of this Evaluation Task study, but is to be fully included within Task X. See footnote 8 on page 13.

11. The sum of all flows into and out of each node must be zero. If any such sum is not zero, it indicates there is a conversion error.
12. Electrical networks are divided into "areas" for administrative purposes. Areas are further subdivided into "zone areas" or "zones". The PG&E Bay Area is an "engineering analysis area" that cuts across numerous administrative areas. In the PG&E system, each "area" includes 2-4 "zones." The PG&E Bay Area system Optimal has been tasked with studying is superimposed on the PG&E administrative areas, and its borders are not congruent with those of the administrative areas -- that is, it consists of a number of zones that are subsets of the "areas" in which system data was provided to Optimal. Moreover, some such zones are "conforming" zones, and are to be included in this Study, while others are "non-conforming" zones, which are not to be included in the Study.

4.3.3 Study Phase 3 - Bay Area System Loading

The principal activity of Phase 3 was to test-load the Bay Area System. Loading consisted of 2 parts.

4.3.3.a First, using load flow, Optimal loaded the un-optimized baseline Bay Area System from Study Phase 1 until collapse.

4.3.3.b Second, Optimal loaded the Aempfast-optimized Bay Area System from Phase 2 until the swing bus generator, MORRO 4, was approximately 25% overloaded.

Results of Study Phase 3 are shown in Table 6 on page 26

4.3.4 Optional Study Phase 4 - Further Bay Area System Improvements

Using Aempfast, it would be feasible to size and place resources to improve the Bay Area System by (1) reducing losses, (2) increasing reliability, and (3) improving the voltage profile levels beyond those indicated in Phase 2 of the Evaluation Task. Such an approach, however, would have required the addition or movement of strategic resources, as indicated by Aempfast. This exercise was not included in the scope of this Evaluation Task study, and accordingly has not been performed here, but is fully included within Task X.

5 Systems Studied

5.1 Data Used

As outlined above, Optimal performed the Evaluation Task study using data provided by the Cal ISO and PG&E.

5.1.1 Data Provided Post August 22, 2001

0614-8750-p7.epc. The California ISO provided this data file. It is of the full WSCC system in ".epc" format. This system consists of approximately 11,688 buses, 10,510 branches, 1,674 generators and 5,504 loads.

5.1.2 Data Partitioned to the PG&E Network

0614-8750-p7.epc. Optimal converted 0614-8750-p7.epc to ".cwf", partitioned it to contain only the PG&E network, and performed initial processing. Partitioning to the PG&E Bay Area System resulted in 2,506 buses, 3,164 branches, 438 generators, and 1,145 loads. The "Bay Area System" is defined by and includes the following conforming PG&E Bay Area Zones:

TABLE 2 Bay Area System by Zones (Data Provided Post-August 22, 2001)

Dataset Processed: Cal ISO file -0614-8750-p7.epc	
ZONE NUMBER	**LOCATION**
307	EAST BAY
308	DIABLO
309	SAN FRANCISCO
310	PENINSULA
316	MISSION
317	DE ANZA
318	SAN JOSE
321	SANTA CLARA
330[a]	

a. Note: Optimal has created “Zone 330” for the purposes of this study. It consists of the buses PLO ALTO, JENNY, and CARTWRT.

6 Review of Processing Steps

6.1 Load Flow: Cal ISO file 0614-8750-p7.epc

Optimal directed its major initial processing activity to the Cal ISO file “0614-8750-p7.epc,” as follows:

6.1.1 Step 1. Data Conversion to “.cwf” Format

Optimal converted the data to “.cwf” format, partitioned it to the PG&E network, and removed all “hanging buses” and “islands”.[13]

6.1.2 Step 2. Load Flow to Establish Base Case (Un-Optimized PG&E System)

Optimal ran the data using Optimal's load flow to establish a base case for later comparisons.

Optimal obtained P losses, flow violations, and a voltage profile.

TABLE 3 Initial Processing of PG&E System Using Load Flow

Dataset:	**0614-8750-p7.epc**
Source:	**California ISO**
Number of Buses:	**2,506**
Number of Branches:	**3,164**
Number of Generators:	**438**
Number of Loads:	**1,145**
Total Generation (MW):	**19,984.3**
Total Load (MW):	**19,054.8**
Total Q Generation (MVAr):	**13,853.0 (Note: Relative Measure)**
P Losses (MW):	**929.5**
Q Losses (MVAr):	**7,604.3**
Swing Generator MORRO 4	
P Capacity:	**340.0 MW**
P Output:	**221.9 MW**
P Capacity Remaining	**181.1 MW**
Q Capacity:	**168.0 MVAr**
Q Output:	**42.8 MVAr**
Q Capacity Remaining:	**125.2 MVAr**
Run Time (seconds):	**25.7**

13. “Hanging” buses are buses that have no load and no generation. They are said to just “hang” on the system. “Islands” are single buses that are listed in the data but are not connected to the system.

6.2 Aempfast Optimization and Analysis: Cal ISO file -0614-8750-p7.epc

Optimal ran the data applying the Aempfast Optimizer in a single pass-through (“Study Phase 1 - Initial Load Flow” on page 17). This optimized the network without the addition of new active (P) or reactive (Q) resources.

TABLE 4 Initial Optimization of PG&E System Using Aempfast

Dataset:	**0614-8750-p7.epc**
Source:	**California ISO**
Number of Buses:	**2,506**
Number of Branches:	**3,164**
Number of Generators:	**438**
Number of Loads:	**1,145**
Total Generation (MW):	**19,908.7**
Total Load (MW):	**19,054.8**
Total Generation (MVAr):	**12,706.0 (Note: Relative Measure)**
P Losses (MW):	**853.9**
Improvement in P Losses (MW):	**75.6 (8.1%)**
Q Losses (MVAr):	**6,457.3**
Improvement in Q Losses (MVAr):	**1.147.0**
Swing Generator MORRO 4	
P Capacity:	**340.0 MW**
P Output:	**146.3 MW**
P Capacity Remaining	**193.7 MW**
Q Capacity:	**168.0 MVAr**
Q Output:	**72.0 MVAr**
Q Capacity Remaining:	**96.0 MVAr**
Power Quality Improvement:	**2% (estimated)**
Run Time (seconds):	**7.8**

Notes re 5.2 and Table 4:

6.2.0.a The Aempfast optimized data was given a final run through load flow to assure that “before” and “after” Aempfast comparisons have been performed fairly, using the same display method.

6.2.0.b The single Aempfast Optimization pass reduced Bay Area System P losses from 929.5 MW [see Table 3 on page 19] to 853.9 MW, an improvement of 75.6 MW, or greater than 8% (eight percent). This also has the effect of reducing system generation required to meet load by an amount equal to the reduced losses, i.e., from 19,984.3 MW [see Table 3 on page 19] to 19,908.7 MW.

6.2.0.c Aempfast has made a definable improvement in the overall PG&E System and has eliminated the risk of collapse anywhere within the PG&E System (not only the Bay Area).

6.2.0.d There is a significant reduction in Q losses as compared with the base case. The single optimization pass reduced the Q losses by 1,147 MVAr (7,604.3 - 6,457.3

MVAr). This reduction in losses results in a significant increase in system MVAr resources that is critically important in fighting voltage collapse.

6.2.0.e The “Power quality improvement” is a rough estimation based on improvements to (1) the PG&E system’s voltage profile, (2) power flows in the System, and (3) the System’s resistance to voltage collapse.

6.3 Additional Processing

6.3.1 Convergence

The original PG&E Bay Area System data showed some resistance to smooth convergence. One of the many objective functions Optimal has selected and built into the Aempfast optimizer is “minimize P losses and minimize Q losses”. As a default function, however, Aempfast always enforces voltage limits; and it has the unique capability of simultaneously analyzing, improving, and optimizing the subject network. As the network voltage profile improves, flow mismatches tend to be reduced. This results in smoother power flow, faster convergence of both load flow and Aempfast, and improved overall system health. Optimization and analysis using Aempfast produces an overall and meaningful improvement in system reliability and power quality. As overall network health is increased, stress on the system is reduced, and network efficiency is increased -- often dramatically.

7 Results From Final Phase of the Study

The results of the Evaluation Task study show that Aempfast optimization led to (i) a significant reduction in PG&E system losses, (ii) a noticeable improvement in load flow run time, and (iii) improvement in the Bay Area system voltage profile to one that reflecting a system with a greater ability to resist voltage collapse.

7.1 Augmented Scope of Work: Criteria for Loading of the Bay Area

Optimal’s Additional Task 4 was to increase the load in the PG&E Bay Area System as it stood on June 14, 2000 in a manner that maintains power factors (PF) at consistent levels, and to determine the magnitude of load shedding required to protect the network against voltage collapse under the increased load. In addition Optimal was asked to identify the best location on the PG&E system at which to monitor for indication of approaching voltage collapse.

In the July 24 meeting the Technical Reviewers also requested that the P and Q load case be run into heavy overload on the June 14, 2000 PG&E Bay Area System swing generator MORRO 4 (36410) (Additional Task 5). Optimal has executed these additional study exercises.

The procedures and results are discussed in Section 8 on page 21, and Table 5 on page 24 and Table 6 on page 26.

8 Discussion of Study Results

Optimal established the base case for the Evaluation Task using a load flow run on the original data provided by Cal ISO/PG&E, as is shown in the section [6.1.2] entitled, “Step 2. Load Flow to Establish Base Case (Un-Optimized PG&E System)” on page 19“.

Optimal also has provided Table 5, “Aempfast PG&E System Optimization Gains Comparison,” on page 24 to show non-technical reviewers a fair Before and After comparison of Aempfast capabilities at 100% Bay Area System load.

8.1 Analysis Using Traditional Load Flow Tools

Using traditional load flow tools, Optimal increased Bay Area system P and Q loads on the un-optimized June 14, 2000 PG&E System, maintaining constant power factors, until system voltage collapse occurred. See Table 5, below. At collapse, 59.8 MW of generation capacity remained available in the PG&E System. At collapse the system consumed 375.6 MVAr above reactive power (Q) consumed at the base case. This increase in system MVAr loss accelerated the system voltage collapse. At system collapse, the NEWARK D bus (30630), a high voltage PG&E System backbone bus, had dropped to 216 kV, an extremely sharp drop (12 kV, or over 5%, down from 228 kV) for such a key bus. A pending voltage collapse is indicated at the 225 - 227 kV level. This indicates that 227 kV is the reasonable voltage level at which to begin load shed. Optimal confirms from this data that the unplanned June 14 blackout event was the result of voltage collapse, and not the result of a demand overload relative to overall available PG&E System generating capacity. Optimal concludes that the actions Cal ISO and PG&E took on June 14, 2000 to prevent Bay Area System collapse were the best that could be taken based on the traditional analytical tools their engineers then had available.

8.2 Analysis Using Aempfast

As summarized above, using traditional analytical tools, Cal ISO and PG&E were unable to identify and effectively resolve system congestion and related conditions that inhibited power flows needed to maintain voltage stability at critical points of the System, including the Bay Area, on June 14, 2000. Using Aempfast, however, Optimal confirmed that on that date the PG&E System had sufficient generation and other system resources, if properly adjusted and controlled, to withstand voltage collapse in the Bay Area.

Optimal applied Aempfast's Optimizer to identify (1) the sources of such congestion and related conditions on the June 14, 2000 PG&E Bay Area System, and (2) specific, easily-accomplished measures for alleviating such conditions and assuring adequate power flows throughout the System to maintain voltage stability. The primary solutions involved simple "re-controlling" (i.e., adjusting the controls) of the PG&E System "control buses" available to Cal ISO at the time. (Four hundred and twelve (412) of the total of 2506 buses on the PG&E System are identified and used as "control buses" through which the Bay Area System is monitored and managed.) [Note: In addition, the Aempfast Optimizer identified one smaller PG&E System generator that was causing congestion and could have been shut down to improve system power flows. For the purpose of this study, the generator was left running (i.e., unchanged from the data supplied).] Aempfast optimization did not add any system generation or other resources as "system mitigations."

8.2.1 Stress Testing: Apply Increased P&Q Load to 100% of Rated System Capacity

Aempfast initial optimization of the June 14, 2000 PG&E System resulted in improved system power flows, in a noticeable reduction in network losses, in an improvement in voltage profile, and in an increase in available PG&E System generation resources. After Aempfast optimization, the Bay Area System was stable not only under the June 14, 2000 loads but also under test loads Optimal subsequently applied of up to 130.4 MW above the June 14, 2000 load levels, as follows:

On the un-optimized PG&E System, Optimal was able (using load flow) to increase the load on the Morro 4 generator (the "swing" generator for the system that day) by only 58.4 MW, from the base case level of 221.9 MW (see Table 3) to a level of 280.2(+) MW, at which point the system failed under voltage collapse. This 58.4 MW increase on Morro 4 increased total system P generation from the base case level of 19,984.3 MW (see Table 3) to a level of 20,042.6 MW at collapse point. At the point of collapse, system load was 19,085.2 MW, or only 30.4 MW above the base case load of 19,054.8 MW. This means that only 30.4 MW (approximately 48%) of the 58.4 MW of increased Morro 4 generation actually reached the load at the time of collapse, with the rest consumed by system losses -- a clear sign of an unhealthy system. System P losses increased by 27.9 MW, from the base case level of 929.5 MW to a total of 957.4 MW at system collapse.

Morro 4 has a rated capacity of 340.0 MW. At the system collapse point, it was loaded only to 280.2 MW with 59.8 MW of capacity still unused and inaccessible.

After Aempfast optimization the Bay Area System was secure against voltage collapse. The MORRO 4 generator, as the swing bus, could be loaded to its full rated capacity of 340.0 MW, rather than just to 280.2 MW, with an increase in total available PG&E system generation to 20,102.4 MW. This optimization outcome alone results in a direct gain of 59.8 MW in available PG&E System generating capacity over the un-optimized base case System.

Moreover, Aempfast optimization reduced the PG&E system P losses to 886.8 MW. This is 42.7 MW below the base case P losses of 929.5 MW (Table 3), and 70.6 MW below the 957.4 MW of P losses occurring on the system at the point of collapse (Table 5).

Comparing the post-optimization and the pre-optimization cases, Aempfast optimization resulted in an increase in P generation available to the System of 59.8 MW (from 20,042.7 MW to 20,102.4 MW), and a decrease in system P losses of 70.6 MW (957.4 MW to 886.8 MW). Thus, the total improvement in P available to the System after optimization is 130.4 MW (59.8 MW + 70.6 MW). This potentially allows load within the Bay Area portion of the System to increase by 130.4 MW (increase in total system load from 19,085.2 MW to 19,215.6 MW), rather than by only 30.4 MW, the increase in P load on the un-optimized system at point of voltage collapse.

In the after-optimization case, with the swing generator loaded at 100% of rated P capacity, there was 81.2 MVAr of Q capacity still available on the swing generator. This indicates the ability of the swing generator to be loaded above its rated MW value -- a case presented in Section 7.2.2. Moreover, the optimized system with the swing generator at full P load also maintains a significant reduction in system Q losses (765.1 MVAr) below the Q loss levels in the un-optimized system base case (7,604.3 - 6,839.2 MVAr). This increased availability of Q resources in the optimized system makes it significantly more resistant to voltage collapse, even at significantly increased loads.

8.2.1.1 Aempfast PG&E System Optimization Gains (Comparison of Un-Optimized System at Collapse Point With Optimized System At Full Load)

TABLE 5 Aempfast PG&E System Optimization Gains Comparison

	Dataset Processed: Cal ISO file -0614-8750-p7.epc	
Before Aempfast Optimization	**On Un-Optimized PG&E System: Increase P Load to Point of System Collapse**	
	Total P generation [base case:19,984.3 MW]	= 20,042.7 MW
	Increase in P generation at collapse	= 58.4 MW
	P load at collapse [base case: 19,054.8 MW]	= 19,085.2 MW
	P load increase [base case: 19,054.8 MW]	= 30.4 MW
	P losses [base case 929.5 MW]	= 957.4 MW
	Increase in P losses at collapse	= 27.9 MW
	Q increase [relative to base case, Table 3]	= 6.8 MVAr
	Q losses at collapse [base case 7,603 MVAr]	= 7,979.9 MVAr
	Q losses increase at collapse	= 375.6 MVAr
	Generator MORRO 4[a]	
	P output [base case 221.9 MW] at collapse	= 280.2 MW
	P generation capacity unused at collapse	= 59.8 MW
	Q output [base case 42.8 MVAr] at collapse	= 52.6 MVAr
	Q capacity unused at collapse	= 115.4 MVAr
	Point of System Collapse (PG&E System Failure)[b] = 280.2 MW	
	Voltage on NEWARK D bus (30630)	= 216.0 kV
After Aempfast Optimization	**On Optimized PG&E System: Increase P load to 100% of Swing Generator Capacity (System Does Not Collapse)**	
	Total P generation available	= 20,102.4 MW
	P load	= 19,215.6 MW
	P losses	= 886.8 MW
	Q increase	= 35.8 MVAr
	Q losses	= 6,839.2 MVAr
	Swing Generator MORRO 4	
	P output	= 340.0 MW
	P capacity (rated) remaining at Morro 4	= 0 MW
	Q output	= 86.8 MVAr
	Q capacity remaining	= 81.2 MVAr
	System Does Not Collapse at Full Rated Loading of Swing Generator	
	Voltage on NEWARK D bus (30630)	= 226 kV
	SYSTEM COMPARISONS, BEFORE AND AFTER OPTIMIZATION[c]	
	Morro 4 P generation output improvement	**= 59.8 MW(21.34%[d])**
	Reduction in P losses [957.4 MW - 886.8 MW]	**= 70.6 MW(7.4%)**
	Total System Improvement in available P	**= 130.4 MW**
	Reduction in Q losses [7,979.9 - 6,839.2]	**= 1,140.7 MVAr**
	Approximate Increase in Power Quality	**= 2%**

a. Swing Generator; Capacity: P 340.0 MW; Q 168 MVAr

b. The PG&E system is at collapse -- not just the Bay Area System.

c. This assumes the “Before” condition is just prior to PG&E System collapse (failure). Although the Aempfast-optimized “After” condition can still be safely overloaded (see After Aempfast Optimization section in Table on page 26), without Aempfast the PG&E System proceeds to failure. The difference in Power Quality at this point is infinite.

d. Improvement over Morro 4 swing generator output at system collapse (280.2 MW)

8.2.2 Stress Testing: Safely Overloading the PG&E Bay Area System

8.2.2.1 Apply Increased P & Q Load in Bay Area 125% Greater Than Swing Generator Rated P Capacity

Cal ISO asked Optimal to run a stress test for voltage stability of the Aempfast-optimized system by applying P and Q load increases in the Bay Area to levels overloading the rated P capacity of the swing generator (Morro 4) (340.0 MW). Optimal arbitrarily selected and applied a 3% increase in the P and Q loads for the Bay Area system, while maintaining power factor (PF) in all loads.[14] The 3 percent increase in P load in the Bay Area System resulted in a total load on the Morro 4 swing generator of 423.8 MW, 83.8 MW (24.6%) over its rated capacity.

Even under this additional Bay Area stress loading, voltage collapse did not occur on the Aempfast-optimized System. A principal reason for this is that in the optimized PG&E System, Q losses continue to be controlled even as P load and Q load are increased by 3 percent. The Q losses for the optimized system with the swing generator at 125% P generation (7,033.2 MVAr) are 571.1 MVAr less than Q losses in the un-optimized base case (7,604.3 MVAr). Through optimization (Table 4 on page 20) the system gained 571.1 MVAr, while losing only 50.8 MVAr in Q load vis-a-vis the base case. This represents a net gain of 520.3 MVAr (571.1 - 50.8 MVAr) in Q resources available in the system to defeat voltage collapse. Results are shown in Table 6 on page 26.

For purposes of comparison, Table 6 on page 26 includes data describing conditions on the PG&E System at the point of the simulated June 14, 2000 system collapse. At collapse, the Bay Area load had increased by 30.4 MW over the un-optimized PG&E base line system (Table 3 on page 19), or approximately 0.4% of the Bay Area load (approximately 7,603 MW in the conforming portions of the Bay Area). This comparison demonstrates the greatly increased stability and robustness of the Aempfast optimized PG&E System of that date, which could have accommodated significantly increased Bay Area P and Q loading without system voltage collapse.

14. Optimal used 7,603.3 MW as the P load for the Bay Area System, conforming zones; an increase of 3% equaled 228.1 MW. Optimal used 1693.3 MVAr as the Q load for the Bay Area System; an increase of 3% equaled 50.8 MVAr.

TABLE 6 Aempfast PG&E System Optimization Overloading Comparison

	Dataset Processed: Cal ISO file -0614-8750-p7.epc	
Before Aempfast Optimization	**For Comparison: Collapse Case: Increase Un-Optimized Bay Area System P & Q Loads By 0.4%, to System Collapse Point**	
	P increase to collapse point	= 30.4 MW
	P losses at collapse	= 957.5 MW
	System P load at collapse	= 19,085.2 MW
	Q increase to collapse point	= 6.8 MVAr
	Q losses at collapse	= 7,979.9 MVAr
	Generator MORRO 4[a]	
	P output at collapse	= 280.2 MW
	P capacity unused at collapse	= 59.8 MW
	Q output at collapse	= 52.6 MVAr
	Q capacity unused at collapse	= 115.4 MVAr
	At Collapse Point [PG&E System Failure][b]	**= YES**
	Voltage on NEWARK D (30630) bus	= 216.0 kV
After Aempfast Optimization	**Increase Optimized Bay Area System P & Q Loads By 3.0%**[c]	
	P load increase in Bay Area	= 228.1 MW
	Increased System P load	= 19,282.9 MW
	System P losses	= 903.3 MW
	Q load increase in Bay Area	= 50.8 MVAr
	System Q losses	= 7,033.2 MVAr
	Swing Generator MORRO 4 (36410), At 3% Increased Bay Area P and Q Loads (Overload to 125% of Swing Generator Capacity)	
	P output	= 423.8 MW (24.6% Overload)
	P capacity remaining	= -83.8 MW[d]
	Q output	= 98.7 MVAr
	Q capacity remaining	= 69.3 MVAr
	System Does Not Collapse Under 3% Bay Area P and Q Load Increases	
	Voltage on NEWARK D (3060) bus	= 226 kV

a. Values are repeated from Table 5, first section. MORRO 4 (36410) swing bus generator is rated at 340 MW and 168 MVAr.

b. The PG&E System is at collapse -- not just the PG&E Bay Area System.

c. Increases are applied to Table 4 values (PG&E System after initial Aempfast optimization).

d. Negative value represents amount of overload.

8.3 Discussion of Aempfast and its Application in the Evaluation Task

Aempfast was designed primarily for complex, non-linear network analysis and optimization. The Evaluation Task Scope of Work focused primarily on performing analytic tasks rather than on system optimization. Optimal understands that analysis also is a significant and integral part of true power system optimization. Optimal has included numerous analytical features in Aempfast so that it can be used to address many different objectives and apply many different constraints on a network, while optimizing the subject network.

The constraints Aempfast addresses include both "equality constraints" (that is, fixed and ascertainable values; e.g., "Per schedule, this generator must produce exactly 200 MW of power"; or "These various loads are known to be exactly, in the aggregate, 1453 MW.") and "inequality constraints" (that is, constraints expressed as "limits" that fluctuate dynamically within a permissible range in a functioning system, e.g., voltage limits and Q limits). Approximately 70% of the constraints that operate within power systems are in the form of inequality constraints or "dynamic limits". The prevalence of inequality constraints in power systems, together with the inability of prior algorithmic approaches to address such fluctuating limits in a fast, practicable, accurate manner, has persistently bedeviled power system analysis, planning, and operation, and previously has altogether precluded true electric power system optimization.

The novel capability of Aempfast is that it quickly and accurately, without linearization of what is very fundamentally a nonlinear power system, addresses both equality and inequality constraints. Not only is Aempfast able to enforce limits on dynamically fluctuating constraints, a unique capability in itself, but it is able to do so vigorously.

Optimal's purpose in developing Aempfast was to overcome the principal shortcoming of other known tools claiming to be power system "optimizers" -- that is, their inability to address and manage, or enforce, limits. Generally, other tools marketed as "optimizers" attempt to overcome such shortcomings by changing inequality constraints into equality constraints. They do this by assigning fixed values for "optimization" purposes to factors that in actual power networks in fact are dynamically varying factors. By definition, every such approach misrepresents every subject power system, and therefore defeats the possibility of conducting a true system optimization.

The first question posed for this Evaluation Task study asked Optimal to rank loads in the PG&E System according to their effective benefit to the system as load shed measures. This first question of the Evaluation Task, therefore, is an exercise simply in ranking loads, which are equality constraints. After the initial optimization, the analytical features of Aempfast reported that all loads in the Bay Area System were poorer choices for load shed than loads in other areas of the PG&E system, as load shed at any level was unnecessary in the Bay Area under an optimized system.

Aempfast first optimizes a power system to establish an optimized base line system, and then outputs records that form the analytical tool for subsequent Aempfast analyses. Thus, in general Optimal executes the Aempfast Optimizer on a subject system first, and then follows with Aempfast analyses applied to the optimized system.

This is the procedure Optimal used in the Evaluation Task. First, Optimal ran Aempfast on the system data supplied by Cal ISO to optimize the PG&E System, in order to establish the System data needed for analysis: Optimal specified the "limits" of operation and Aempfast then successfully optimized the PG&E System against those limits. In this instance, Aempfast achieved successful first-run Bay Area system "optimization" because on June 14, 2000 the PG&E System, which previously had not been subjected to what Optimal considers a "true optimizer," [i.e., an optimizer capable of accurately addressing "inequality constraints"], in fact had sufficient system resources to allow such optimization (system adjustments to reduce congestion and related problems, reduce system losses, and meet system and Bay Area P and Q load requirements) without the need for adding resources. Again, the progressive functionality of Aempfast is its ability to quickly and accurately optimize and analyze systems against the dynamically varying limits characteristic of power systems.

The Aempfast Optimizer lowered June 14, 2000 PG&E System P and Q losses significantly, and improved the voltage profile -- that is, it improved the Bay Area System's ability to meet the voltage limits required for system stability. It did this using only the generation, transmission, and distribution resources already present on the System. Aempfast also improved overall PG&E Bay Area System stability by removing significant congestion and related conditions that restricted power flow and led directly to voltage collapse.

A key factor in the optimized PG&E Bay Area System's increased voltage stability is the Aempfast Optimizer's success in reducing Q (reactive power) losses in the initial optimization (1,147 MVAr less power loss than in the un-optimized base case June 14, 2000 PG&E System), and in controlling Q losses (i.e., preserving system Q resources) in subsequent scenarios. In the scenario, for example, in which Optimal increased P and Q loads in the Bay Area by 3%, pushing the swing generator to 125% of its rated capacity, Aempfast in effect used 579.5 of the 1,147 MVAr gained in optimization to fight system voltage collapse under the higher P load, and still held a net 520.2 MVAr of the initial optimization savings "in reserve" to benefit the system. This net system gain in Q resources represents a significant improvement to the PG&E System.

As a result, after Aempfast Bay Area System optimization, no possibility of voltage collapse under prevailing June 14, 2000 generation and load conditions remained -- even when Optimal subsequently increased load, for test purposes, to levels above Bay Area System capacity on that date.

Appendix A: Excerpts from EOB/CPUC Report to Governor Davis

This section presents excerpts from the report entitled “CALIFORNIA'S ELECTRICITY OPTIONS AND CHALLENGES - REPORT TO GOVERNOR GRAY DAVIS” that are relevant to the June 14, 2000 unscheduled rolling blackouts.

CALIFORNIA'S ELECTRICITY OPTIONS AND CHALLENGES

REPORT TO

GOVERNOR GRAY DAVIS

Michael Kahn
Chairman
Electricity Oversight Board

Loretta Lynch
President
California Public Utilities Commission

November 2000

...

The events giving rise to this Report started with ISO calls for widespread interruption of industrial and other large customers on May 22, 2000, and the imposition of rolling blackouts in the Bay Area on June 14, 2000. Beginning in May 2000, costs for power in all regions and economic sectors of California increased by billions of dollars. On several days in the second quarter of the year, reliability was significantly compromised. The appearance that reliability has been compromised makes all the more distressing the huge run-up in prices - Californians are paying a lot more for a lot less, in terms of service...

On June 14, PG&E was required to intentionally interrupt nearly 100,000 customers (residential and small business) for the first time in its history. This remarkable event was not related to insufficient supply in the ISO control area as a whole. Rather, it was related to grid instability in the Bay area. The transmission grid operates at a load level of 230,000 volts, with small deviations. If supply and demand get too far out of balance, the entire system can crash, possibly spreading throughout the interconnected grid in the West.

The Bay area grid instability was related to high loads and short supplies in that area, which could not be relieved given the design of the transmission system...

On June 14 the Bay Area suffered unusually hot weather for June, with San Francisco peaking at 103 degrees. Hot weather contributed directly to a record-setting peak load for June of 43,300 MW, system wide. PG&E peaked at 23,361 MW not counting the customers interrupted.

On June 14, import capacity on the transmission system was limited, in order to keep the voltage levels on the grid stable. These import limitations reflected both technical constraints in Northern California and events outside the state. The loss of generation in the Northwest and work being done by Bonneville Power Administration on the British Columbia Hydroelectric Tie limited California's ability to import power.

Voltage instability related to... import limitations, power plants out, and record temperatures set the stage for disaster on June 14, 2000. At 7:30 a.m. the ISO announced that it would request PG&E to curtail 500 MW of interruptible customers beginning at 1200 hours to help correct voltage problems. Reactive support at the transmission and distribution levels was also required of PG&E and the municipalities (Silicon Valley Power, Northern California Power Agency (NCPA), Alameda and Palo Alto).

The critical point below which a system crash becomes imminent is 225,000 volts. Late in the morning, the ISO determined that firm load dropping was imminent and requested PG&E to man all substations. In order to avoid a voltage crash in the Bay Area, the Newark Substation had to maintain a voltage of 228 kV. At 1313 hours, the Newark Substation dropped to 227,000 volts and headed toward 226,000 volts. This triggered the ISO's request for firm load shedding by PG&E. The following blocks were shed:

Block Number	Duration of Outage	Number of Customers	Number of MW
1A	1313 to 1435	33,763	143.9
1B	1430 to 1535	17,616	132.1
1D	1530 to 1635	9,586	29.4
2A	1530 to 1635	36,064	115.5
Total	**1313 to 1635**	**97,029**	**420.9**

Once Block 1A was shed, by contract NCPA shed 3 MW at Palo Alto and 1 MW at Alameda. In a cooperative action, Silicon Valley Power offered to interrupt its non-firm customers, totaling 5 MW beginning at 1400 hours. In order to reduce further curtailments, the ISO loaded key 500/230 kV transformers and transmission lines either near or exceeding their ratings. The firm load shed caused voltage levels to stabilize and averted a wider event.

The ISO issued a Stage 1 Emergency Notice throughout its system, due to a projected operating reserve of 5.3 percent beginning at 1:00 p.m., remaining in effect until 2000 hours. All firm load was restored by 4:35 p.m. with interruptible load restored at 6 p.m...